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Visualization of structures and cosmic flows in the Local Universe

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Abstract. A visualization of three-dimensional structures and cosmic flows is presented using information from the Extragalactic Distance Database V8k redshift catalog and peculiar velocities from the Cosmicflows-1 survey. Structures within a volume bounded at 8000 km/s on the cardinal Supergalactic axes are explored in terms of both the display of the positions of the 30124 galaxies of the catalog and its reconstructed luminosity density field, corrected to account for growing incompleteness with distance. Cosmography of the Local Universe is discussed with the intent to identify the most prominent structures, including voids, galaxy clusters, filaments and walls. The mapping also benefits from precise distance measures provided through the Cosmicflows-1 observational program. Three-dimensional visualizations of the coherent flows of galaxies in the nearby universe are presented using recent results obtained on the reconstruction of cosmic flows with the Wiener Filter approach. The three major components of the Milky Way motion, namely the expulsion from the Local Void, the infall toward the Virgo Cluster, and the bulk flow of the historic Local Supercluster toward the Great Attractor are illustrated using different visualization techniques and analyzed in the light of the cosmography derived from the V8k redshift and Cosmicflows-1 distance catalogs.

Keywords. atlases; distances and redshifts; large scale structures of universe

1. Introduction

The visualization of three-dimensional structures and cosmic flows is a critical ingredient of research into the cosmography of the Local Universe. The purpose of cosmography is to characterize the morphology of features pertaining to the hierarchy of cosmological structures such as voids, groups, clouds, sheets, clusters, filaments, chains, superclusters, and walls. Since structures at all scales are not static in the Hubble flow, cosmography also has to deal with kinematic information.

Maps that assume relative distances based on galaxy redshifts are distorted from true 3D positions. The analysis of cosmic flows in the context of the spatial distribution of charted structures involves identification of attractors and other sources of motions. In turn, the reconstruction of flows provides new insights on their source density field. In this context, accurate determinations of distances and the peculiar velocity of galaxies are required.

2. The COSMIC FLOWS Project

The objective of the COSMIC FLOWS Project is to improve our knowledge of the cosmography of the nearby universe, with an emphasis on the identification of attractors. A key issue is to measure the radial component of the galaxies deviant motion from the Hubble cosmic expansion. The radial peculiar velocity V_{pec} is expressed as a function of the velocity relative to the CMB background, the distance d and the value of the Hubble Constant H_0 : $V_{pec} = V_{CMB} - d * H_0$. Within 10 Mpc, the Cepheid Period-Luminosity

relation, the Tip of the Red Giant Branch method and the Surface Brightness Fluctuation luminosity indicators provide measurements of the distances with 10% accuracy. Further up to 200 Mpc, the galaxy neutral HI gas luminosity-rotation rate Tully-Fisher correlation gives distance measurements with an accuracy of $\sim 20\%$. HI observations most recently have been conducted using the NRAO 100-meter diameter Robert C. Byrd Green Bank Telescope, complemented in the southern sky with the Parkes Telescope. The photometry is acquired with several systems including the University of Hawaii 2.2m Telescope. A first release of measurements of distances and peculiar velocities of 1797 galaxies was achieved with the *Cosmicflows-1* Catalog presented in Tully *et al.* (2008). A three-dimensional velocity and density reconstruction of these peculiar velocities using the Wiener Filter technique was presented in Courtois *et al.* (2012).

3. The Extragalactic Distance Database Catalogs

Our study of the cosmography of the Local Universe benefits from the catalogs made available through the Extragalactic Distance Database presented in Tully *et al.* (2009). Besides the *Cosmicflows-1* Catalog, the *V8k* Catalog consists in 30124 galaxies with redshift found within 8000 km/s along each axis of the supergalactic coordinate system defined by de Vaucouleurs *et al.* (1991). To account for the distortions caused by the influence of the Virgo cluster, redshift positions within 3000 km/s are adjusted following a numerical action flow model. Redshift distortions associated with virial velocities within clusters are also corrected.

A weakness in the use of these catalogs consists in their growing incompleteness with distance. A description that takes this bias into account is offered by the reconstruction of the luminosity density field obtained by smoothing the distribution of galaxies corrected with a Schechter function, as described in Courtois *et al.* (in preparation).

4. Cosmographical maps of the Local Universe

Cosmography calls upon the tools of visualization. An assembly of individual galaxies forms a cloud of points, each one possibly attached with a pointing velocity vector. Reconstructed density fields are described on uniform grids, visualized with several techniques such as isosurface reconstruction. Velocity fields are visualized using vectors or streamlines. To address these needs, the SDvision interactive visualization software is designed to explore structures and cosmic flows in three dimensions, and produce maps and exploratory movies, as illustrated in Fig. 1.

One of the most striking feature in the structure of the Local Universe is the dense concentration of galaxies identified by de Vaucouleurs (1956) that in large measure defines the equator of the Supergalactic coordinate system. Galaxies in this plane, at SGZ=0, are displayed in Fig. 2 (left). The Milky Way, located at the center, belongs to the Local Supercluster whose main component is the Virgo Cluster. A dense filament connects Virgo to the region of the Centaurus Cluster, as can be further appreciated in the other projection shown in Fig. 2 (right). At a distance similar to Virgo Cluster but at negative SGY lies the Fornax Cluster. At 7000 km/s along the positive SGY axis lies the Great Wall which includes the Coma Cluster. At intermediate distances on the scale considered here, we find three major concentrations labelled Pavo-Indus, Perseus-Pisces, and the Southern Wall. In terms of cosmography, another striking feature is the presence of voids with dimensions as large as 5000 km/s. These two maps are affected with the growing incompletness with distance. This is corrected in the three-dimensional map offered in Fig. 1, which illustrate the preponderance of the Great Wall as the most important structure of the Local Universe, and the relatively low importance of our Local Supercluster. Visualizations of the reconstructed velocity field in the nearby Universe are presented in Fig. 3 together with a high-density isosurface reconstructed from the *V8k* catalog. From

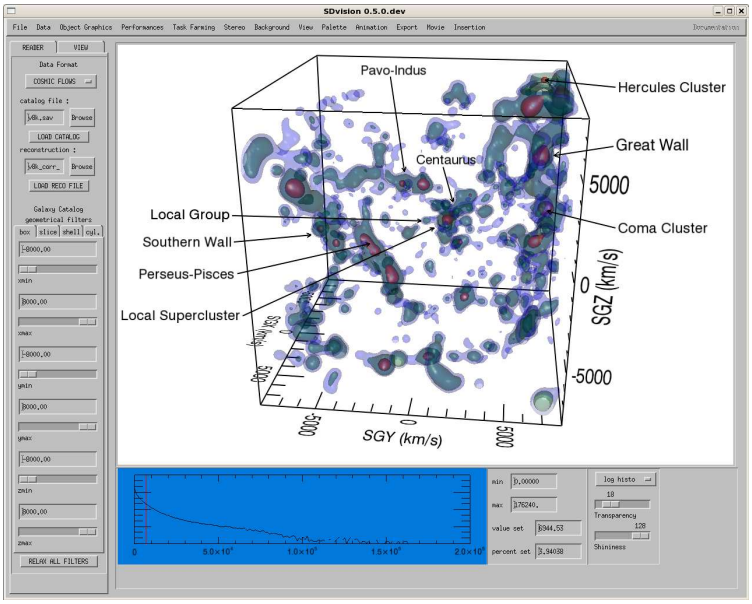

Figure 1. Visualization of the *V8k* Catalog smoothed density field with SDvision using multiple semi-transparent isosurfaces and providing some elements of cosmography.

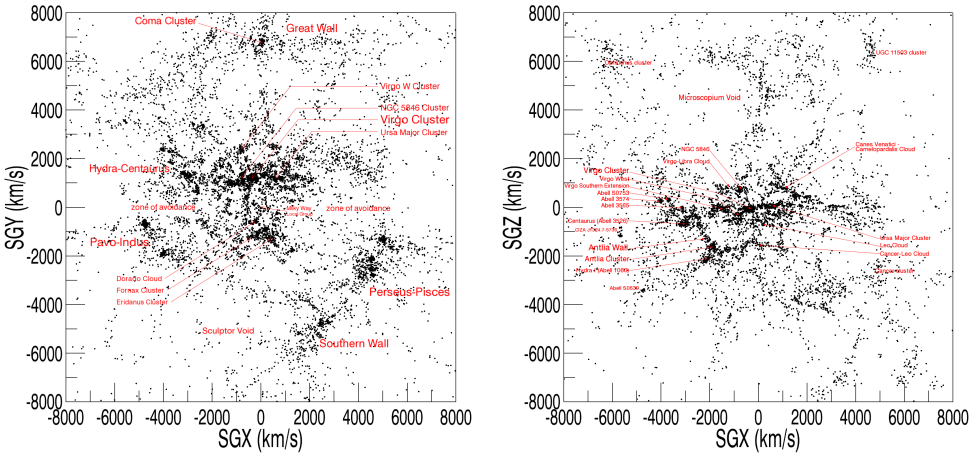

Figure 2. Slices of the Local Universe. These two projections display the distributions of galaxies for $-1000 \leqslant \mathrm{SGZ\ (km/s)} \leqslant 1000$ (left) and $500 \leqslant \mathrm{SGY\ (km/s)} \leqslant 2500$ (right).

these maps, we can infer the presence of a major attractor in the region of the Centaurus Cluster. Cosmic flows visualized as streamlines seeded in the SGX=0 plane are displayed in Fig. 4. This map also shows the underlying density field colored from black (underdense) to red (overdense), the *V8k* galaxies, and the *Cosmicflows-1* galaxies with radial peculiar velocities attached (blue and red arrows for inward and outward moving galaxies, respectively). This map reveals the presence of the very underdense "Local Void" in the immediate vicinity of the Milky Way. This void is seen in both the distribution of galaxies and in the reconstructed source field. The map illustrates the clearing from the voids in the form of outbound flows, as already reported in Tully *et al.* (2008). The map also reveals that the Milky Way is caught in a flow toward the Virgo Cluster, associated mostly with the Virgo gravitational infall. Other attractors and convergent flows seen in this map are discussed in Courtois *et al.* (in prep).

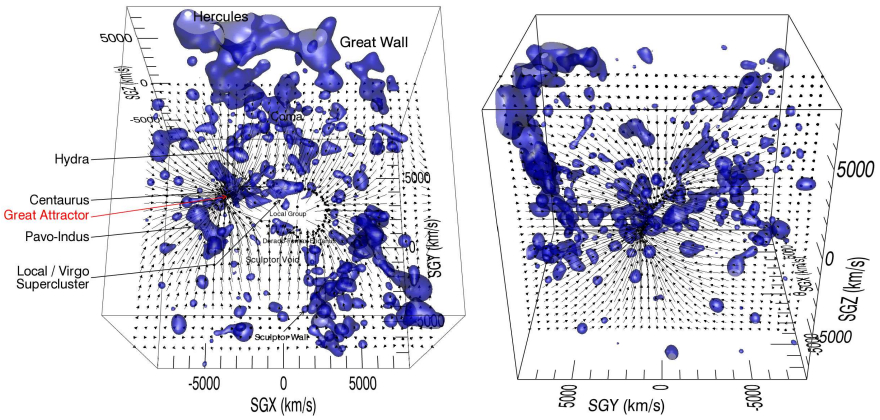

Figure 3. Visualization of the *Cosmicflows-1* reconstructed velocity field on the Supergalactic Plane SGZ=0 (left) and on the SGY-SGZ plane going through the Centaurus Cluster (right).

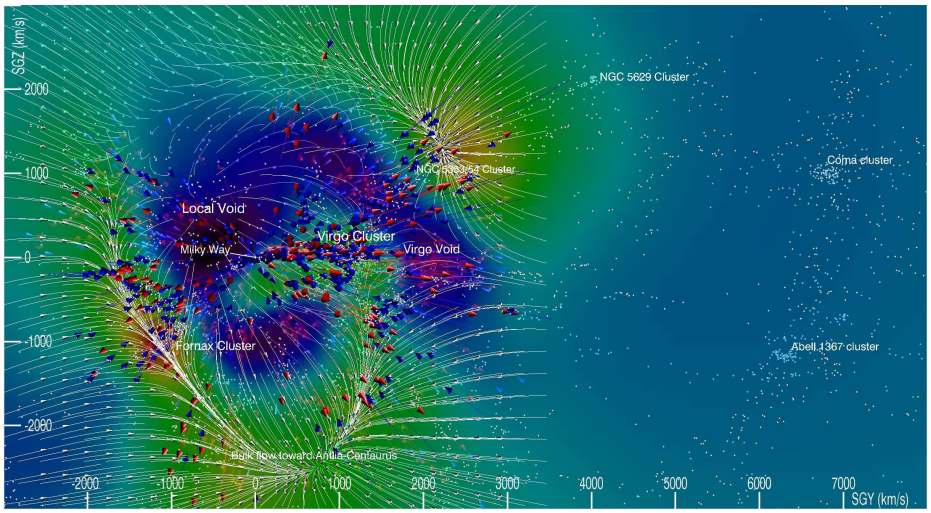

Figure 4. Visualization of structures and cosmic flows in the SGX=0 plane

5. Conclusions and perspectives

The comparative visualization of three-dimensional structures and flows enrich the study of the cosmography of the Local Universe. A more detailed discussion will be presented in Courtois *et al.* (in preparation). New observations being currently aggregated in the *Cosmicflows-2* Catalog will provide distances up to 10,000 km/s. Reconstructions will extend our vision of cosmography to even larger scales.

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